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by

James P. Barrett and Leland J. Goldsmith

NEW HAMPSHIRE
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Acknowledgements

Data for this study came from the New Hampshire plots of the Hatch 149 project entitled "Effects of Site and Stocking on the Growth of Eastern White Pine", a cooperative study made jointly by the Universities of Maine, Massachusetts, and New Hampshire, and the Northeastern Forest Experiment Station of the Forest Service (USDA). The Soil Conservation Service (USDA) classified the soils on each plot. The authors wish to acknowledge the work of Peter H. Allen in establishing the plots, Charles Breeding in classifying the soils on each plot, Robert Joly in analyzing the soil-site data, and William B. Leak in suggesting some data analyses. Computations were run on the IBM 360/50 system at the University of New Hampshire.

Predicting Growth of Eastern White Pine

by James P. Barrett† and Leland J. Goldsmith

Eastern white pine (Pinus strobus L.) accounts for about one-fifth of the standing board-foot volume in New Hampshire. As with other species, variations in white pine stand volume, height, and growth are related to stand and site conditions. The purpose of this study is to provide information so that a forester can predict: (1) site index, (2) cubic-foot volume, (3) board-foot volume, (4) cubic-foot growth, (5) board-foot growth, and (6) mortality for even-aged extensively managed white pine stands.

Annual growth predictions and mortality were based on plot measurements over a nine-year period. Stand height and stand volume predictions were based on the plot establishment data. Yield predictions previously published by Barrett and Allen (1966) and Leak et al. (1970) were also based on the plot establishment data.

Field Methods

Field data were obtained from 65 semi-permanent field plots. These plots were located in essentially pure white pine stand, with at least 80 percent of the overstory basal area in white pine, and ranged from $\frac{1}{20}$- to $\frac{1}{5}$-acre in size. Twelve plots were as small as $\frac{1}{20}$ acre; these plots were located in young and very dense stands. The condition of both the stand and site within and surrounding each plot was judged to be uniform over an area of about $\frac{1}{2}$-acre. Within this $\frac{1}{2}$-acre, the stand was even-aged, with the overstory white pine varying no more than 10 years in age. There had not been any major disturbance to the stands over the past 15 years and only light disturbance within the past six years.

An attempt was made to select plots that gave as wide a range as possible in age, site index, and basal area. The distribution of these 65 plots by breast-height age and initial basal area per acre of overstory pine trees (3.0 inches d.b.h. and larger) is shown in Table 1. Distribution of plots by 10-foot site-index classes is shown in Table 2.

† Associate Professor and graduate student respectively.

Table 1. Distribution of Field Plots by Breast-height Age Class and Initial Basal Area Per Acre of Overstory Pine Trees (3.0 inches d.b.h. and over)

Stand Age (years)	Basal Area Per Acre (sq. ft.)			
	90–150	151–210	211+	Total
	Number of Plots			
16–35	6	6	3	15
36–70	4	23	13	40
71 +	1	7	2	10
Total	11	36	18	65

Table 2. Distribution of Field Plots by 10-foot Site-index Classes (breast-height age 50)

Site-index Class	Number of Plots
50	1
60	33
70	25
80	6
Total	65

Measurements taken on field plots included:

1. An initial tally of all overstory trees 3.0 inches diameter breast-height (d.b.h.) and larger by species, crown class, and d.b.h. Trees in the understory that appeared to represent a younger age class than the main stand were excluded.

2. Initial breast-height age, crown class, total height, diameter outside bark (d.o.b.) and diameter inside bark (d.i.b.) of the bole at 17.3 feet above ground for 10 to 20 sample white pine trees per plot.

3. Remeasurement tallies every 3 years for a total of 9 years after the initial tally. These measurements included diameter breast height for all trees 3.0 inches d.b.h. and larger, and total height for the sample trees.

4. Soil-site descriptions on each plot including soil drainage classification, aspect, slope, exposure, and surface rockiness or stoniness. Soil description was based on information obtained from a pit dug in the center of the most representative soil of the plot. The soil type was then identified and each horizon was carefully described as to texture, structure, color, thickness, and presence of gleyed material. Pint samples were taken from each prominent horizon for subsequent laboratory analysis of texture. No chemical analyses were performed. Soil-site descriptions conformed to those outlined in *Soil Survey Manual* (1951 with supplement issued May 1962).

Soil-Site Prediction of Stand Height

The important relationship between soil characteristics and tree growth has been apparent for many years. The complex relationship between site quality for various tree species and soil factors has been the point of concern of a number of excellent investigations. These studies have deepened the understanding of tree growth and have provided a considerable amount of useful knowledge to forest managers and landowners.

It is important to note, however, that any soil-site study must necessarily concentrate on only a limited portion of the total environmental influence. Careful and complete evaluation of site quality must take into consideration factors of climate, management, diseases and injuries, competition, forest composition, and species as well as soil characteristics. Nevertheless, an investigation of soil characteristics within a limited climatic region on uncut, natural stands can provide insight into site quality evaluation.

A total of 109 sample plots were used in regression analyses to predict average dominant-codominant stand height in terms of age and soil-site variables. These data included plot data from the 65 plots in the growth study supplemented by plot data from 44 plots provided by the Soil Conservation Service.

The model used for predicting average height of dominant-codominant trees in terms of various independent variables was:

$$\text{Log}_{10}\ \text{Height} = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_k x_k + e \qquad \text{Model 1}$$

where: $x = 1/\text{age}$

x_2 to x_k = various soil-site characteristics including:

- Natural drainage class
- Thickness of A horizon
- Thickness of A + B horizons
- Depths to A and B
- Soil p^H
- Soil structure of B horizon
- Texture class of A and B horizons
- Percent clay in A and B horizons
- Percent silt plus clay in A and B horizons
- Percent coarse fragments greater than 2 mm. in B horizon
- Percent slope
- Aspect and exposure of the site
- Surface rockiness or stoniness
- Stratification
- Family textural classification

e = the increment by which any individual dependent observation may fall off the regression surface (called error)

Although many variables approached significance (5-percent level), only two proved significant. They were:

1. Total age (at breast height)
2. Natural drainage class

The regression solution to Model 1 was:

$$\text{Log}_{10}\ \text{Height} = 2.083 - 12.775\ x_1 - .008\ x_2 - .024\ x_3 + .018\ x_4 + .024\ x_5$$

where: x_1 = 1/age
x_2 = 1 if excessively drained; 0 if not
x_3 = 1 if somewhat excessively drained; 0 if not
x_4 = 1 if well drained; 0 if not
x_5 = 1 if moderately well drained; 0 if not
Coefficient of determination (R^2)† = .85
Standard error in percent = 2.2

The solution to the equation is given in Table 3. (Soil drainage classes are described in Appendix 1.) Dominant-codominant stand height is given for a breast-height age of 50 years, and thus is defined as site index. The poorest growth occurs on the somewhat excessively drained soils where site index averages about 64 feet. It is important to note that soils classified as somewhat excessively drained were shallow and might retain less moisture for tree roots than excessively drained soils where site index averages 66 feet. Site index increases to 70 feet for well drained soils and to 71 for moderately well-drained soils. Then site index drops to 67 feet for poorly drained soils. Under the present scheme of drainage classification it is difficult to point the optimum moisture condition for growth, for it is likely included somewhere within the broad category of "poorly drained". Had a finer delineation of moisture conditions within this category been used, it is probable that a somewhat poorly drained site would be well suited for white pine growth as indicated by Husch and Lyford (1956). Note that site index ranges from only 64 to 71 feet—a narrow range when compared to soil-site studies for species in other regions.

Table 3. Predicted Site Index in Terms of Drainage Classification

Drainage Class	*Site Index*
Excessively drained	66 ft. (24 plots)
Somewhat excessively drained	64 ft. (10 plots)
Well drained	70 ft. (46 plots)
Moderately well drained	71 ft. (16 plots)
Poorly drained	67 ft. (13 plots)

Summarizing Stand Plot Data

Plot volumes were computed using volume equations for individual trees, site-index curves, and methods described by Leak et al. (1970). Cubic-foot volume was computed for trees 3.0 inches d.b.h. and larger to a 3.0-inch inside-bark top. Board-foot volume (International ¼-inch rule) was computed for trees 9.0 inches d.b.h. and larger to a 6.0-inch

† Coefficient of determination and standard error (expressed as a percent of the mean) are described by Draper and Smith (1966).

inside-bark top. Volumes per acre were computed for each plot from the initial data and the nine-year data. Periodic annual growth per acre was computed as follows:

$$\text{Periodic annual growth per acre} = \frac{(9 \text{ year volume}) - (\text{initial volume})}{9}$$

Other variables were computed from the initial data. These consisted of:

(1) Mean breast-height age
(2) Site index based on breast-height age 50 years
(3) Basal area per acre for trees 3.0 inches d.b.h. and larger
(4) Basal area per acre for trees 9.0 inches d.b.h. and larger
(5) Mean stand total height based on dominant-codominant trees
(6) Total live trees per acre
(7) Mean Girard form class
(8) Stocking percent as described by Leak et al. (1970)

Stand Volume Tables

Stand volumes can be predicted from variables that are easily measured and are considered representative of the entire stand. Thus a forester can predict stand volume per acre without determining volumes of individual trees. This study provided adequate data to develop regression equations for both cubic-foot and board-foot volume estimates per acre.

The dependent and independent variables were derived from the plot data. Cubic-foot and board-foot volumes per acre were related to basal area per acre, mean dominant-codominant stand height, and mean Girard form class. Basal area per acre used in the cubic-foot volume per acre regression was for trees 3.0 inches d.b.h. and larger. Basal area per acre used in the board-foot volume per acre regression was for trees 9.0 inches d.b.h. and larger.

The model for estimating cubic and board foot volume per acre was:

$$\text{Log}_{10}(\text{Volume per Acre}) = b_0 + b_1 (\text{Log}_{10} BA) + b_2 (\text{Log}_{10} H) + b_3 (\text{Log}_{10} GFC) + e \quad \text{Model 2}$$

where: BA = basal area per acre
H = mean stand height of dominant-codominant trees
GFC = mean Girard form class
e = error

This model was based on variables described by Bruce and Schumacher (1950) for predicting volume per acre.

For cubic-foot volume per acre the regression solution to Model 2 was:

$$\text{Log}_{10}(\text{Cubic-foot volume per acre}) = -1.836 + 1.042 (\text{Log}_{10} BA) + .387 (\text{Log}_{10} H) + 1.324 (\text{Log}_{10} GFC)$$

where: Coefficient of determination (R^2) = .958
Standard error = .84%

The solution to the cubic foot volume per acre equation is shown in Table 4.

Table 4. Cubic-foot Volume Per Acre for Trees 3.0 Inches d.b.h. and Larger to a 3.0-inch d.i.b. top, as Related to Basal Area Per Acre in Square Feet, Height in Feet, and Girard Form Class

Ht.	GFC	BASAL AREA PER ACRE (3-inch Trees and Larger)							
		90	120	150	180	210	240	270	300
		CUBIC-FOOT VOLUME PER ACRE							
40	65	1662	2242	2830	3422	4018	4618	5221	5827
	70	1833	2474	3121	3775	4432	5094	5759	6428
	75	2008	2710	3420	4136	4856	5581	6310	7043
	80	2187	2952	3725	4505	5290	6079	6873	7671
	85	2370	3199	4036	4881	5732	6587	7448	8312
50	65	1811	2445	3085	3730	4380	5035	5692	6353
	70	1998	2697	3403	4115	4832	5554	6279	7007
	75	2189	2955	3728	4509	5294	6085	6879	7678
	80	2385	3218	4061	4911	5767	6628	7493	8363
	85	2584	3488	4401	5321	6249	7182	8119	9062
60	65	1944	2624	3310	4003	4701	5403	6108	6817
	70	2144	2894	3652	4416	5185	5960	6738	7520
	75	2349	3171	4001	4838	5681	6530	7382	8239
	80	2559	3454	4358	5270	6188	7112	8041	8974
	85	2773	3743	4722	5710	6706	7707	8713	9724
70	65	2063	2785	3514	4249	4990	5735	6484	7236
	70	2276	3072	3876	4687	5504	6326	7152	7982
	75	2494	3366	4247	5136	6031	6931	7836	8746
	80	2716	3666	4626	5594	6569	7549	8535	9526
	85	2944	3973	5013	6062	7118	8180	9249	10322
80	65	2173	2933	3700	4475	5254	6039	6828	7620
	70	2397	3235	4082	4936	5796	6662	7531	8405
	75	2626	3544	4472	5408	6351	7299	8252	9210
	80	2861	3861	4871	5891	6917	7950	8988	10031
	85	3100	4183	5279	6383	7495	8614	9739	10869
90	65	2274	3069	3873	4683	5500	6321	7146	7975
	70	2509	3386	4272	5166	6067	6972	7883	8798
	75	2749	3710	4681	5660	6647	7639	8637	9639
	80	2994	4041	5099	6165	7240	8321	9407	10499
	85	3244	4378	5525	6681	7845	9016	10194	11376
100	65	2369	3197	4034	4878	5728	6584	7443	8307
	70	2613	3527	4450	5381	6319	7262	8211	9164
	75	2863	3864	4876	5896	6923	7957	8996	10040
	80	3119	4209	5311	6422	7541	8667	9799	10936
	85	3379	4561	5755	6959	8171	9391	10618	11850

For board-foot volume per acre (International ¼-inch rule) the regression solution to Model 2 was:

$$\text{Log}_{10}\text{ (Board foot volume per acre)} = -3.24 + .983\ (\text{Log}_{10}\text{BA}) + 1.43\ (\text{Log}_{10}\text{H}) + 1.501\ (\text{Log}_{10}\text{GFC})$$

where: Coefficient of determination (R^2) = .993
Standard error = .64%

The solution to the board foot volume per acre equation is shown in Table 5.

Table 5. Board-foot Volume Per Acre for Trees 9.0 Inches d.b.h. and Larger to a 6-inch d.i.b. Top, as Related to Basal Area per Acre in Square Feet, Height in Feet, and Girard Form Class

Ht.	GFC	BASAL AREA PER ACRE (9-inch Trees and Larger)							
		60	90	120	150	180	210	240	270
		BOARD-FOOT VOLUME PER ACRE							
40	65	3311	4933	6546	8151	9751	11347	12939	14527
	70	3701	5514	7316	9110	10899	12682	14461	16236
	75	4105	6115	8114	10104	12088	14066	16039	18008
	80	4523	6737	8940	11132	13318	15497	17670	19839
	85	4953	7379	9791	12193	14586	16973	19354	21729
50	65	4556	6788	9006	11215	13417	15612	17802	19987
	70	5092	7586	10066	12535	14996	17449	19897	22339
	75	5648	8414	11164	13903	16632	19353	22068	24777
	80	6223	9270	12300	15317	18324	21322	24313	27297
	85	6816	10153	13472	16776	20069	23353	26629	29897
60	65	5914	8810	11689	14556	17413	20263	23105	25941
	70	6609	9846	13064	16269	19462	22647	25823	28993
	75	7331	10921	14490	18044	21586	25118	28641	32157
	80	8076	12032	15964	19880	23782	27673	31555	35428
	85	8846	13178	17485	21773	26047	30309	34561	38803
70	65	7372	10982	14572	18146	21708	25260	28803	32339
	70	8240	12275	16287	20281	24262	28232	32192	36144
	75	9139	13614	18064	22494	26910	31313	35705	40088
	80	10068	14999	19901	24782	29647	34498	39337	44165
	85	11027	16428	21797	27143	32471	37784	43084	48373
80	65	8923	13293	17638	21964	26276	30575	34863	39143
	70	9973	14857	19713	24549	29367	34172	38966	43749
	75	11061	16479	21864	27227	32572	37901	43217	48522
	80	12187	18155	24088	29997	35885	41756	47613	53458
	85	13348	19884	26383	32855	39303	45734	52149	58551
90	65	10560	15732	20874	25994	31096	36184	41259	46324
	70	11803	17583	23330	29052	34755	40441	46114	51774
	75	13091	19502	25875	32222	38547	44854	51145	57423
	80	14422	21485	28507	35500	42468	49416	56348	63265
	85	15796	23532	31223	38882	46514	54124	61716	69292
100	65	12278	18290	24268	30221	36152	42068	47968	53857
	70	13722	20442	27124	33776	40406	47017	53612	60193
	75	15220	22673	30083	37462	44815	52148	59462	66761
	80	16768	24979	33143	41272	49374	57452	65511	73552
	85	18365	27359	36301	45204	54077	62925	71752	80559

Annual Volume Growth Estimation

As with the stand volume per acre equations, growth rates can be predicted by easily measured variables that are representative of the entire stand. Periodic annual cubic-foot and board-foot-volume growth per acre were obtained from 9-year growth data.

Gross and net periodic annual cubic-foot, and gross and net periodic annual board-foot volume growth per acre were developed to predict growth rates. In determining these growth equations, several models were considered that were compatible with equations from growth studies of other eastern conifers (Clutter, 1963 and Nelson, 1963). Net volume growth constitutes 9-year volume of the live trees minus the initial volume; gross volume growth constitutes 9-year volume of the live trees plus the volume of the mortality trees minus the initial volume. Gross volume growth can also be expressed as that volume growth of only those trees that live.

Periodic annual net growth and periodic annual gross growth can be represented by the equations:

$$\text{Periodic annual net growth} = \frac{(\text{9-year volume of surviving trees}) - (\text{Initial volume of all trees})}{9}$$

$$\text{Periodic annual gross growth} = \frac{(\text{9-year volume of surviving trees}) - (\text{Initial volume of trees that survived at 9 years})}{9}$$

or

$$\text{Periodic annual gross growth} = \frac{(\text{9-year volume of surviving trees}) + (\text{Initial volume of trees that died in 9-year period}) - (\text{Initial volume of all trees})}{9}$$

Gross volume growth is a more realistic measure of potential wood yield than net volume growth because one would expect to conduct thinnings that would utilize the losses of mortality.

Cubic-Foot Growth

The periodic gross annual cubic-foot volume growth per acre equation was based on functions of three variables: mean age (breast-height), site index, and basal area per acre (for trees 3.0 inches d.b.h. and larger). The model for this growth rate is as follows:

$$Y1 = b_0 + b_1 \left(\frac{1}{A}\right) + b_2 \left(\frac{SI \times BA}{100}\right) + b_3 \left(\frac{SI \times BA^2}{1000}\right) + e \qquad \text{Model 3}$$

where:
- Y1 = periodic gross annual cubic foot volume growth per acre
- A = mean age (breast-height)
- SI = site index
- BA = basal area per acre (for trees 3.0 inches d.b.h. and larger)
- e = error

The regression solution to Model 3 was:

$$Y1 = 48.9 - 949.739 \left(\frac{1}{A}\right) + 1.595 \left(\frac{SI \times BA}{100}\right) - .027 \left(\frac{SI \times BA^2}{1000}\right)$$

where: Coefficient of determination (R^2) = .354
Standard error = 20.49%

All variables in this equation were significant or approached significance. The solution to the periodic gross annual cubic-foot volume growth per acre equation is shown in Table 6 and is shown graphically in Figure 1. Table 6 indicates that gross growth increases at ages 20 to 60 years. After 60 years age has a negligible effect on growth.

Table 6. Periodic Gross Annual Cubic-foot Volume Growth Per Acre for Trees 3.0 Inches d.b.h. and Larger to a 3.0-inch d.i.b. Top, as Related to Age in Years, Site Index in Feet, and Basal Area in Square Feet

SI	BA	AGE							
		20	30	40	50	60	70	80	90
		CUBIC-FOOT VOLUME PER ACRE							
60	90	74	90	98	102	106	108	110	111
	120	92	108	116	121	124	126	128	129
	150	108	124	132	137	140	142	144	145
	180	121	137	144	149	152	155	156	158
	210	130	146	154	159	162	164	166	167
	240	137	153	161	166	169	171	173	174
	270	141	157	165	170	173	175	177	178
65	90	80	96	104	108	112	114	116	117
	120	100	116	124	129	132	134	136	137
	150	117	133	141	145	149	151	153	154
	180	131	146	154	159	162	165	166	168
	210	141	157	165	170	173	175	177	178
	240	149	164	172	177	180	183	184	186
	270	153	169	177	181	185	187	189	190
70	90	86	102	110	115	118	120	122	123
	120	108	124	131	136	139	142	143	145
	150	126	142	150	154	158	160	161	163
	180	141	156	164	169	172	175	176	178
	210	152	168	176	181	184	186	188	189
	240	160	176	184	189	192	194	196	197
	270	165	180	188	193	196	199	200	202
75	90	92	108	116	121	124	126	128	129
	120	115	131	139	144	147	149	151	152
	150	135	151	159	163	166	169	170	172
	180	151	166	174	179	182	185	186	188
	210	163	179	187	191	194	197	198	200
	240	171	187	195	200	203	205	207	208
	270	176	192	200	205	208	210	212	213
80	90	98	114	122	127	130	132	134	135
	120	123	139	147	151	155	157	159	160
	150	144	160	167	172	175	178	179	181
	180	161	176	184	189	192	195	196	198
	210	174	189	197	202	205	208	209	211
	240	183	199	206	211	214	217	218	220
	270	188	204	212	216	220	222	224	225

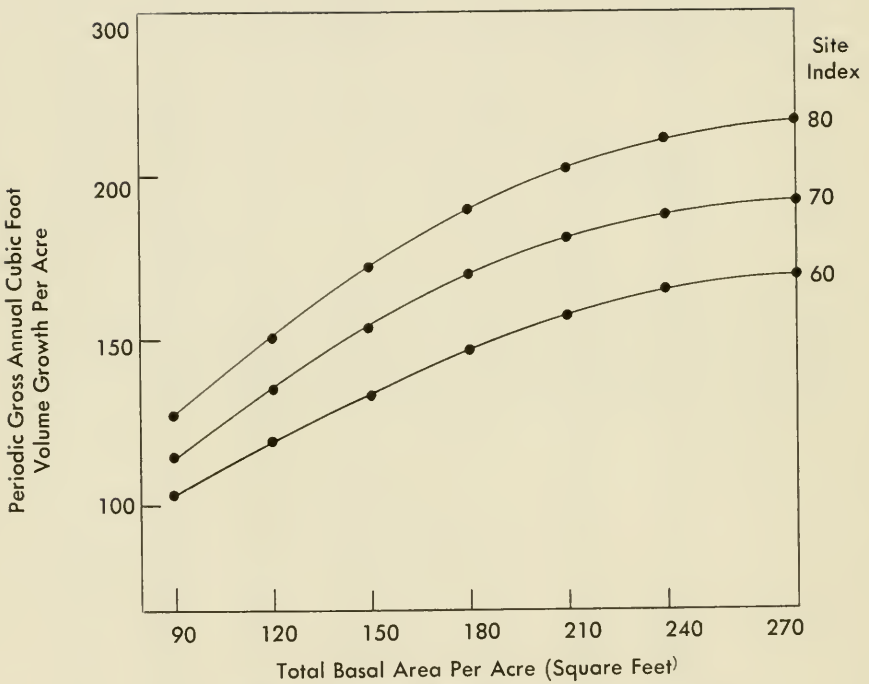

Figure 1. Periodic Gross Annual Cubic-foot Volume Growth Expressed as a Function of Site Index and Basal Area Per Acre at Age 50

The periodic net annual cubic foot volume growth per acre equation was based on functions of four variables: mean age (breast-height), site index, basal area per acre (for trees 3.0 inches d.b.h. and larger), and total stems per acre. Total stems per acre was used in this equation because it accounted for the fairly high mortality of trees in the smaller size classes. The model for this growth rate is as follows:

$$Y2 = b_0 + b_1\,(TS) + b_2\,(BA) + b_3\left(\frac{BA^2}{100}\right) + b_4\left(\frac{SI}{A}\right) + e \qquad \text{Model 4}$$

where:
- Y2 = periodic net annual cubic-foot volume growth per acre
- TS = total live stems per acre
- BA = basal area per acre (for trees 3.0 inches d.b.h. and larger)
- SI = site index
- A = mean age (breast-height)
- e = error

The regression solution to Model 4 was:

$$Y2 = -56.0 - .132\,(TS) + 2.135\,(BA) - .501\left(\frac{BA^2}{100}\right) + 7.444\left(\frac{SI}{A}\right)$$

where: Coefficient of determination (R^2) = .674
Standard error = 48.05%

Although the site index and age interaction (SI/A) variable was not significant, it was retained because it does not appear biologically sound to develop a model for predicting growth without site index and age. All other variables in this equation were significant (5-percent level). The high standard error results from volume loss due to mortality which is only partially influenced by age, site, and density. The solution to the periodic net annual cubic-foot volume growth per acre equation is shown in Table 7 and is shown graphically in Figure 2.

Board-Foot Growth

The periodic gross and net annual board-foot volume growth per acre equations were based on functions of four variables: mean age (breast-height), site index, basal area per acre for trees 3.0 inches d.b.h. and larger, and basal area per acre for trees 9.0 inches d.b.h. and larger. The model for these growth rates is as follows:

$$Y3 \text{ or } Y4 = b_0 + b_1\,(P) + b_2\left(\frac{1}{A}\right) + b_3\left(\frac{SI \times BA}{100}\right) + b_4\left(\frac{SI \times BA^2}{1000}\right) + e \qquad \text{Model 5}$$

where:
- Y3 = periodic gross annual board-foot volume growth per acre
- Y4 = periodic net annual board-foot volume growth per acre
- $P = \dfrac{\text{(basal area per acre for trees 9.0 inches d.b.h. and larger)}}{\text{(basal area per acre for trees 3.0 inches d.b.h. and larger)}} \times 100$
- A = mean age (breast-height)
- SI = site index
- BA = basal area per acre (for trees 3.0 inches d.b.h. and larger)
- e = error

Data were analyzed only for the 50 plots with an average tree age of 35 years or older. Plots younger than 35 years contain few trees 9.0 inches d.b.h. and larger that qualify for board-foot growth analysis.

Table 7. Periodic Net Annual Cubic-Foot Volume Growth Per Acre for Trees 3.0 Inches d.b.h. and Larger and to a 3.0-inch d.i.b. Top, as Related to Total Stems Per Acre, Site-index in Feet and Basal Area Per Acre in Square Feet at Age 50 Years

SI	BA	TOTAL STEMS 100	200	300	400	500	600	700	800
		CUBIC-FOOT VOLUME PER ACRE							
60	90	91	78	64	51	38	25	12	—1
	120	123	110	97	84	70	57	44	31
	150	147	134	120	107	94	81	68	54
	180	161	148	135	122	108	95	82	69
	210	167	153	140	127	114	101	87	74
	240	163	150	137	123	110	97	84	71
	270	150	137	124	111	98	84	71	58
65	90	92	78	65	52	39	26	12	0
	120	124	111	98	84	71	58	45	32
	150	148	134	121	108	95	82	68	55
	180	162	149	136	122	109	96	83	70
	210	167	154	141	128	115	101	88	75
	240	164	151	137	124	111	98	85	71
	270	151	138	125	112	98	85	72	59
70	90	92	79	66	53	39	26	13	0
	120	125	112	98	85	72	59	46	32
	150	148	135	122	109	95	82	69	56
	180	163	149	136	123	110	97	83	70
	210	168	155	142	129	115	102	89	76
	240	165	151	138	125	112	99	85	72
	270	152	139	126	112	99	86	73	60
75	90	93	80	67	53	40	27	14	1
	120	126	112	99	86	73	60	46	33
	150	149	136	123	109	96	83	70	57
	180	163	150	137	124	111	97	84	71
	210	169	156	142	129	116	103	90	76
	240	165	152	139	126	112	99	86	73
	270	153	139	126	113	100	87	73	60
80	90	94	81	67	54	41	28	15	1
	120	126	113	100	87	73	60	47	34
	150	150	137	123	110	97	84	71	57
	180	164	151	138	125	111	98	85	72
	210	170	156	143	130	117	104	90	77
	240	166	153	140	126	113	100	87	74
	270	153	140	127	114	101	87	74	61

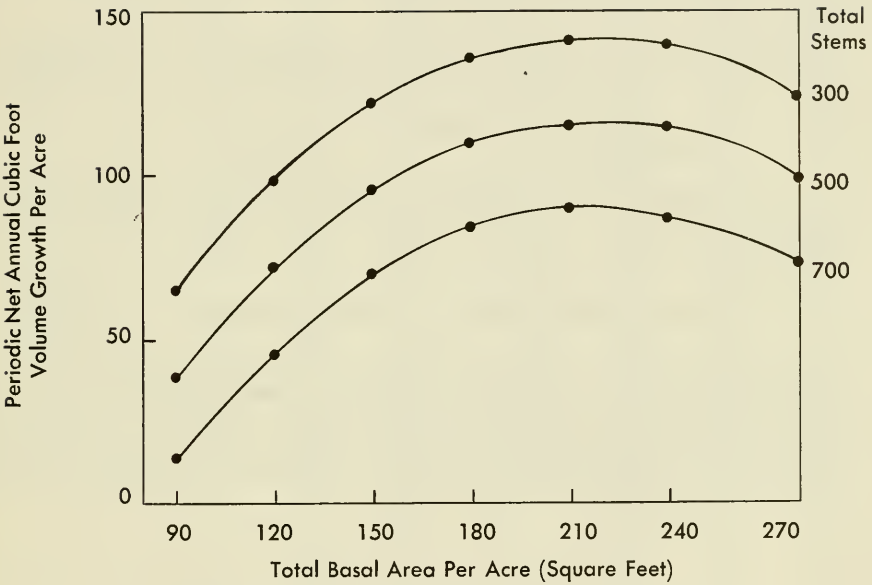

Figure 2. Periodic Net Annual Cubic-Foot Volume Growth Expressed as a Function of Total Stems Per Acre and Basal Area Per Acre at Age 50 and at Site Index 70

For periodic gross annual board-foot volume growth per acre (Y3) the regression solution to Model 5 was:

$$Y3 =$$

$$-381.1 + 7.437\ (P) + 6103.202\ \left(\frac{1}{A}\right) + 9.199\ \left(\frac{SI \times BA}{100}\right) - .125\ \left(\frac{SI \times BA^2}{1000}\right)$$

where: Coefficient of determination (R^2) = .403
Standard error = 23.49%

The solution to the periodic gross annual board-foot volume growth per acre equation is shown in Table 8 and is shown graphically in Figure 3.

For periodic net annual board-foot volume growth per acre (Y4) the regression solution to Model 5 was:

$$Y4 =$$

$$-255.605 + 5.904\ (P) + 4222.069\ \left(\frac{1}{A}\right) + 9.487\ \left(\frac{SI \times BA}{100}\right) - .162\ \left(\frac{SI \times BA^2}{1000}\right)$$

where: Coefficient of determination (R^2) = .273
Standard error = 27.39%

The solution to the periodic net annual board-foot volume growth per acre equation is shown in Table 9 and is shown graphically in Figure 4.

Although site index by basal area squared interaction $\left(\frac{SI \times BA^2}{1000}\right)$ and age variables in both equations were not significant they were retained in the model. All other variables in these equations were significant (5-percent level). Since the percent basal area in sawtimber is fixed at 70 percent, Figures 3 and 4 are apt to be a bit misleading because at very high stand basal areas the percent sawtimber would likely be less than 70.

Table 8. Periodic Gross Annual Board-foot Volume Growth Per Acre for Trees 9.0 Inches d.b.h. and Larger to a 6-inch d.i.b. Top, as Related to Percent of Basal Area in Sawtimber, Site Index in Feet, and Basal Area Per Acre in Square Feet at Age 50 Years

SI	BA	PERCENT OF 9-INCH BA TO 3-INCH BA					
		50	60	70	80	90	100
		BOARD-FOOT VOLUME PER ACRE					
60	90	. . .	623	697	771	846	920
	120	. . .	741	815	890	964	1038
	150	771	846	920	995	1069	1143
	180	863	937	1012	1086	1160	1235
	210	941	1015	1089	1164	1238	1312
	240	1005	1079	1154	1228	1302	1377
	270	1056	1130	1205	1279	1353	1428
65	90	585	659	733	808	882	956
	120	713	787	862	936	1010	1085
	150	826	901	975	1050	1124	1198
	180	925	1000	1074	1148	1223	1297
	210	1010	1084	1158	1233	1307	1382
	240	1079	1154	1228	1302	1377	1451
	270	1134	1209	1283	1358	1432	1506
70	90	621	695	770	844	918	993
	120	759	333	908	982	1057	1131
	150	881	956	1030	1104	1179	1253
	180	988	1062	1137	1211	1285	1360
	210	1079	1153	1227	1302	1376	1451
	240	1154	1228	1302	1377	1451	1526
	270	1213	1287	1362	1436	1511	1585
75	90	657	732	806	880	955	1029
	120	805	880	954	1028	1103	1177
	150	936	1011	1085	1159	1234	1308
	180	1050	1125	1199	1274	1348	1422
	210	1148	1222	1296	1371	1445	1520
	240	1228	1303	1377	1451	1526	1600
	270	1292	1366	1440	1515	1589	1664
80	90	694	768	842	917	991	1065
	120	851	926	1000	1075	1149	1223
	150	991	1066	1140	1214	1289	1363
	180	1113	1187	1262	1336	1410	1485
	210	1217	1291	1365	1440	1514	1589
	240	1303	1377	1451	1526	1600	1674
	270	1370	1445	1519	1593	1668	1742

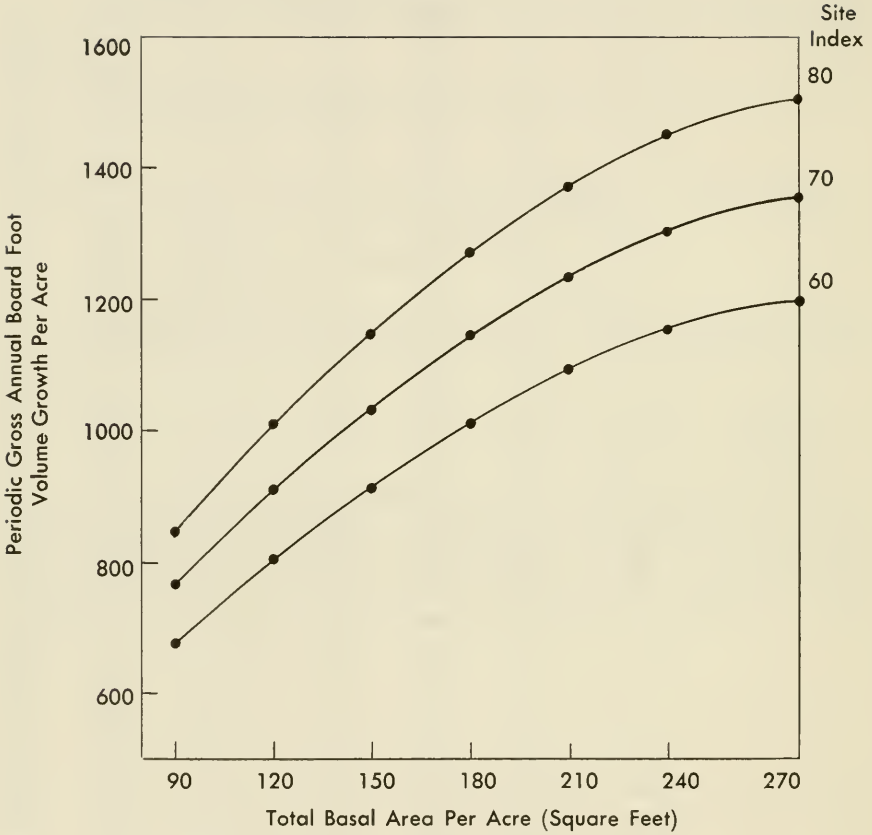

Figure 3. Periodic Gross Annual Board-foot Volume Growth Expressed as a Function of Site Index and Basal Area Per Acre at Age 50 and 70 Percent Basal Area in Sawtimber

Table 9. Periodic Net Annual Board-foot Volume Growth Per Acre for Trees 9.0 Inches d.b.h. and Larger and to a 6-inch d.i.b. Top, as Related to Percent of Basal Area in Sawtimber, Site Index in Feet, and Basal Area Per Acre in Square Feet at Age 50 Years

		PERCENT OF 9-INCH BA TO 3-INCH BA					
SI	BA	50	60	70	80	90	100
		BOARD-FOOT VOLUME PER ACRE					
60	90	. . .	616	675	734	793	852
	120	. . .	726	785	844	903	962
	150	759	818	877	936	995	1054
	180	833	892	951	1010	1069	1128
	210	890	949	1008	1067	1126	1185
	240	930	989	1048	1107	1166	1225
	270	952	1011	1070	1129	1188	1247
65	90	593	652	711	770	829	888
	120	712	771	830	889	948	1007
	150	812	871	930	989	1048	1107
	180	892	951	1010	1069	1129	1188
	210	954	1013	1072	1131	1190	1249
	240	997	1056	1115	1174	1233	1292
	270	1021	1080	1139	1198	1257	1316
70	90	629	688	747	806	866	925
	120	757	816	875	934	993	1052
	150	865	924	983	1042	1101	1160
	180	951	1011	1070	1129	1188	1247
	210	1018	1077	1136	1195	1254	1313
	240	1064	1123	1182	1241	1300	1359
	270	1090	1149	1208	1267	1326	1385
75	90	665	725	784	843	902	961
	120	802	861	920	980	1039	1098
	150	917	976	1036	1095	1154	1213
	180	1011	1070	1129	1188	1247	1306
	210	1082	1141	1200	1259	1318	1377
	240	1131	1190	1249	1308	1368	1427
	270	1159	1218	1277	1336	1395	1454
80	90	702	761	820	879	938	997
	120	848	907	966	1025	1084	1143
	150	970	1029	1088	1147	1207	1266
	180	1070	1129	1188	1247	1306	1365
	210	1146	1205	1264	1323	1382	1441
	240	1199	1258	1317	1376	1435	1494
	270	1228	1287	1346	1405	1464	1523

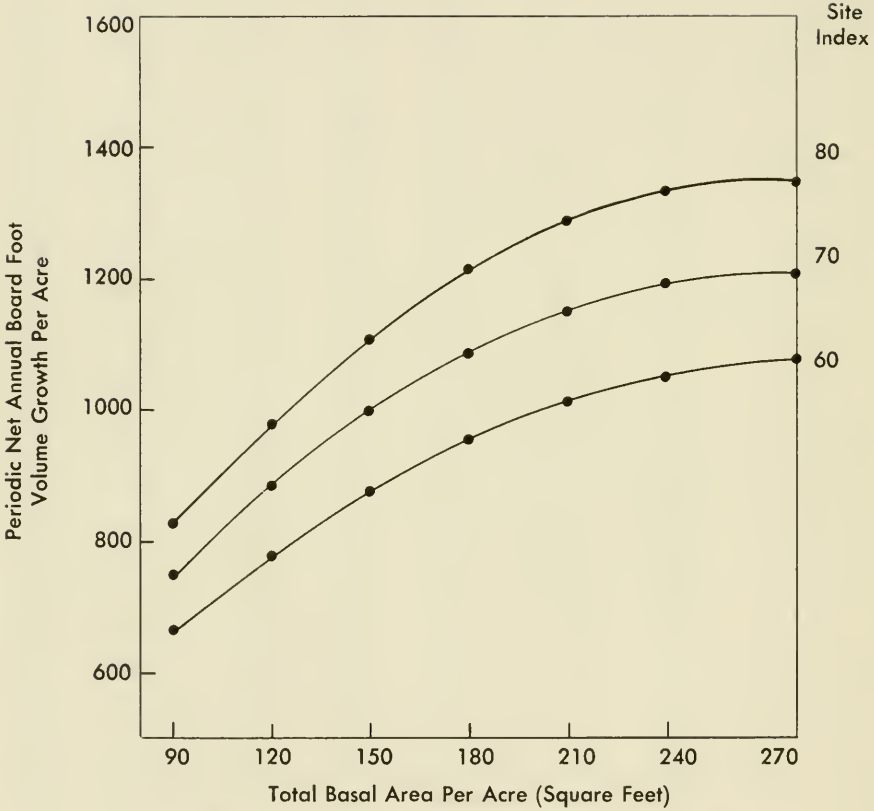

Figure 4. Periodic Net Annual Board-foot Volume Growth Expressed as a Function of Site Index and Basal Area Per Acre at Age 50 and 70 Percent Basal Area in Sawtimber

Mortality

A regression model using mortality, in terms of number of stems per acre per year, as a dependent variable and using functions of three variables: total live stems per acre, mean age (breast-height), and site index was developed as follows:

$$\text{Mortality} = b_0 + b_1 \left(\frac{TS}{A}\right) + b_2 (TS) + b_3 \left(\frac{1}{A}\right) + b_4 (SI) + e \qquad \text{Model 6}$$

where: TS = total live stems per acre
A = mean age (breast height)
SI = site index
e = error

The regression solution to Model 6 was:

$$\text{Mortality} = -15.73 + .646 \left(\frac{TS}{A}\right) + .0223 (TS) - 438.2 \left(\frac{1}{A}\right) + .257 (SI)$$

where: Coefficient of determination (R^2) = .987
Standard error = 31.12%

All variables in this equation were significant. The solution to the equation is shown in Table 10. Mortality increases with increasing age, site index, and total stems per acre. Most of the mortality occurs in the suppressed-intermediate trees.

Table 10. Mortality Per Acre Per Year as Related to Total Live Stems, Site Index in Feet, and Age in Years

SI	Age	LIVE STEMS PER ACRE							
		200	300	400	500	600	700	800	900
		DEAD STEMS PER ACRE							
60	20	0	0	0	5	11	16	21	27
	30	0	0	3	7	11	16	20	25
	40	0	0	4	8	12	16	19	23
	50	0	1	5	9	12	16	19	23
	60	0	2	6	9	12	16	19	22
	70	0	3	6	9	12	16	19	22
	80	0	3	6	9	12	15	19	22
65	20	0	0	1	6	12	17	23	28
	30	0	0	4	8	13	17	21	26
	40	0	2	5	9	13	17	21	25
	50	0	3	6	10	13	17	20	24
	60	0	4	7	10	14	17	20	23
	70	1	4	7	10	14	17	20	23
	80	2	5	8	11	14	17	20	23
70	20	0	0	2	8	13	19	24	29
	30	0	1	5	10	14	18	23	27
	40	0	3	7	11	14	18	22	26
	50	1	4	8	11	15	18	22	25
	60	2	5	8	11	15	18	21	25
	70	2	5	9	12	15	18	21	24
	80	3	6	9	12	15	18	21	24
75	20	0	0	3	9	14	20	25	31
	30	0	2	6	11	15	20	24	28
	40	0	4	8	12	16	20	23	27
	50	2	5	9	12	16	19	23	26
	60	3	6	9	13	16	19	23	26
	70	4	7	10	13	16	19	23	26
	80	4	7	10	13	16	19	22	25
80	20	0	0	5	10	16	21	27	32
	30	0	3	8	12	17	21	25	30
	40	2	5	9	13	17	21	25	28
	50	3	7	10	14	17	21	24	28
	60	4	7	11	14	17	21	24	27
	70	5	8	11	14	17	21	24	27
	80	5	8	12	15	18	21	24	27

An Example

A forester can easily use Tables 4 through 10 in estimating present stand volumes and in predicting growth and mortality. Solutions can also be obtained from the equations, but table values are adequate for most practical purposes. Tables 7, 8, and 9 give growth estimates only for age 50 years; for the equations on which these tables are based, however, age has a small effect on growth estimates.

Table 3 can be used to predict site index from soil drainage classification. If mean dominant-codominant tree height has been estimated, Figure 5 can be used to estimate site index.

Assume a forester collected the following inventory data:

(1) basal area per acre (trees 3.0 inches and larger) = 180 square feet
(2) mean height of dominant-codominant trees = 60 feet
(3) mean breast-height age of dominant-codominant stand = 40 years
(4) mean Girard form class = 80
(5) trees per acre (3.0 inches and larger) = 400
(6) percent pine sawtimber = 60 percent

From Figure 5, site index = 70 feet.

Based on these data the following estimates are made:

Table	Type of Estimate Per Acre	Value
4	Cubic foot volume	5,270
5	Board foot volume	23,782
6	Gross annual cubic foot volume growth	164
7	Net annual cubic foot volume growth	123
8	Gross annual board foot growth	1,062
9	Net annual board foot growth	1,011
10	Annual tree mortality	7

Tables 7, 8 and 9 give growth rates for stands that are at a breast-height age of 50 years. From the equations the growth rates at 40 years are:

Net annual cubic foot volume growth	126
Gross annual board foot volume growth	1,093
Net annual board foot volume growth	1,032

Considering the errors involved in predicting growth, the differences in predicting growth at 40 and 50 years is of little practical importance.

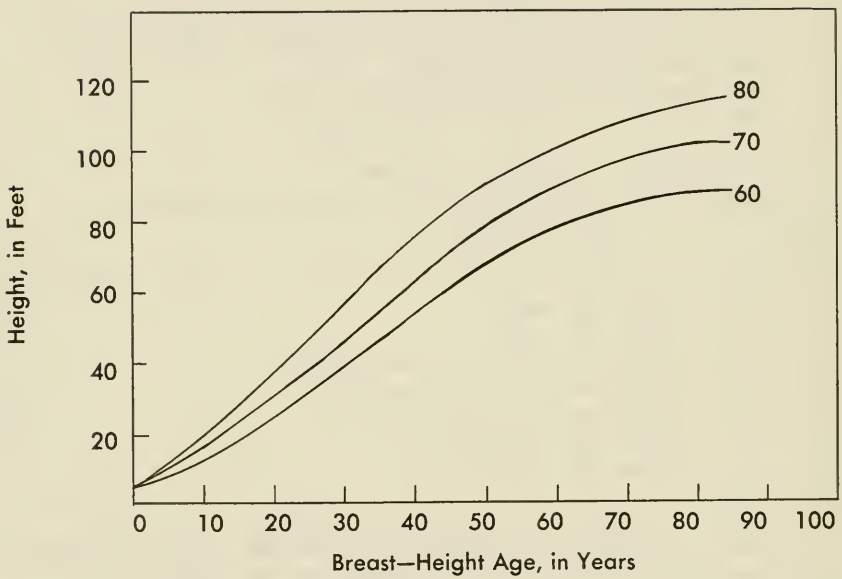

Figure 5. Site-index Curves for Eastern White Pine in New England (b.h. age 50) Based on Frothingham's Site-index Curves Corrected to a Breast Height Age of 50

Conclusions

The results of this study can be used to advantage in interpreting the site, volume, and growth of white pine in southern and central New Hampshire.

The results of the soil-site study indicate that the amount of available moisture as measured by drainage class is the most important factor influencing tree growth (Table 3). Although the dominant-codominant stand height for some plots ranged up to about 80 feet at a breast-height age of 50 years, predicted heights (or site indices) ranged only from 64 to 71 feet.

Moderately precise estimates of stand cubic-foot and board-foot volumes per acre can be obtained from measurements of basal area per acre, dominant-codominant stand height, and average Girard form class (Tables 4 and 5). For cubic-foot volume per acre, basal area per acre is based on all trees 3.0 inches d.b.h. and larger and volumes are computed to a 3.0-inch inside-bark top. For board-foot volume per acre, basal area per acre is based on all trees 9.0 inches d.b.h. and larger and volumes are computed to a 6.0-inch inside-bark top. One would need to make an appropriate reduction in poorer quality white-pine stands where utilization would be to larger top diameters.

Although only fairly precise, estimates of periodic annual cubic foot and board foot volume growth and mortality (Tables 6 through 10) are useful for management planning. Since trees on all study plots were well-spaced, some appropriate reduction in cubic-foot and board-foot growth is needed to allow for openings in natural stands. In addition, sawtimber utilization was computed to a 6.0-inch top inside bark. Just as for the stand volume table, one would need to make an appropriate reduction in growth in poorer quality white pine stands where utilization would be to a larger top diameter.

The equations and tables indicate moderately fast periodic annual growth rates. However, the establishment period for white pine is relatively long (when compared with southern pines). Thus, mean annual growth is considerably lower than periodic annual growth. Growth equations can best be utilized together with "Yields of Eastern White Pine in New England Related to Age, Site, and Stocking" by Leak et al. (1970) in making decisions on the management of white pine.

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APPENDIX I

Soil-Drainage Classes

0. *Very poorly drained.* Water is removed from the soil so slowly that the water table remains at or on the surface the greater part of the time. Soils of this drainage class usually occupy level or depressed sites and are frequently ponded. Very poorly drained soils in the podzolic soil regions commonly have dark-gray or black surface layers and are light gray, with or without mottlings, in the deeper parts of the profile. In the grassland regions, very poorly drained soils commonly have mucky surfaces with distinct evidences of gleying. These soils are wet enough to prevent the growth of important crops (except rice) without artificial drainage.

1. *Poorly drained.* Water is removed so slowly that the soil remains wet for a large part of the time. The water table is commonly at or near the surface during a considerable part of the year. Poorly drained conditions are due to a high water table, to a slowly permeable layer within the profile, to seepage, or to some combination of these conditions. In the podzolic soil region, poorly drained soils may be light gray from the surface downward, with or without mottlings. Among the dark-colored soils of the grasslands, poorly drained soils commonly have slightly thickened dark-colored surface layers. The large quantities of water that remain in and on the poorly drained soils prohibit the growing of field crops under natural conditions in most years. Artificial drainage is generally necessary for crop production, provided other soil characteristics are favorable.

2. *Imperfectly or somewhat poorly drained.* Water is removed from the soil slowly enough to keep it wet for significant periods but not all of the time. Imperfectly drained soils commonly have a slowly permeable layer within the profile, a high water table, additions through seepage, or a combination of these conditions. Among the podzolic soils, somewhat poorly drained soils are uniformly grayish, brownish, or yellowish in the upper A horizon and commonly have mottlings below 6 to 16 inches in the lower A and in the B and C horizons. Among the dark-colored soils of the grasslands, somewhat poorly drained soils have thick, dark A horizons, high in organic matter, and faint evidences of gleying immediately beneath the A horizon. The growth of crops is restricted to a marked degree, unless artificial drainage is provided. This is the lowest drainage class in which a zonal soil retains enough of its characteristics to be classed in that order. Many soils with this drainage class cannot be placed in the zonal order.

3. *Moderately well drained.* Water is removed from the soil somewhat slowly, so that the profile is wet for a small but significant part of the time. Moderately well drained soils commonly have a slowly permeable layer within or immediately beneath the solum, a relatively high water table, additions of water through seepage, or some combination of these conditions. Among podzolic soils, moderately well drained soils have uniform colors in the A and upper B horizons, with mottling in the lower B and in the C horizons. Among the dark-colored

soils of the grasslands, profiles have thick, dark A horizons and yellowish or grayish faintly mottled B horizons.

4. *Well drained.*—Water is removed from the soil readily but not rapidly. Well-drained soils are commonly intermediate in texture, although soils of other textural classes may also be well drained. Among the podzolic soils, well-drained soils are free of mottlings (except for fossil gley), and horizons may be brownish, yellowish, grayish, or reddish. They may be mottled deep in the C horizon or below depths of several feet. Among the dark-colored soils of the grasslands, well-drained soils have thick, dark A horizons, reddish, brownish, or yellowish B horizons, and C horizons that may or may not be mottled. Well-drained soils commonly retain optimum amounts of moisture for plant growth after rains or additions of irrigation water. This is the characteristic drainage of modal representatives of the zonal great soil groups.

5. *Somewhat excessively drained.* Water is removed from the soil rapidly. Some of the soils are lithosolic. Many of them have little horizon differentiation and are sandy and very porous. Among podzolic soils, somewhat excessively drained types are free of mottling throughout the profile and are brown, yellow, gray, or red. Among the dark-colored soils of the grasslands, many profiles have relatively thin A horizons, brownish, yellowish, grayish, or reddish thin B horizons, and no mottlings within the solum. Only a narrow range of crops can be grown on these soils, and the yields are usually low without irrigation.

6. *Excessively drained.* Water is removed from the soil very rapidly. Excessively drained soils are commonly Lithosols or lithosolic, and may be steep, very porous, or both. Shallow soils on slopes may be excessively drained. Among podzolic soils, excessively drained types are commonly brownish, yellowish, grayish, or reddish in color and free of mottlings throughout the profile. Among the dark-colored soils of the grasslands, profiles commonly have thin A horizons (except for sand types that may have thick ones). Enough precipitation is commonly lost from these soils to make them unsuitable for ordinary crop production.